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To: Dr. D. Mills
Director of Research

TRIP REPORT: VISIT TO THE CENTRE FOR ENGINEERING SYSTEMS ADVANCED RESEARCH AT ORNL ON FEBRUARY 21, 1989

S.B. Nickerson

Evangelos Milios (Department of Computer Science, University of Toronto), Narinder Bains (AECL Advanced Systems), and Bruce Nickerson (Electrical Research) visited the Centre for Engineering Systems Advanced Research (CESAR) at Oak Ridge National Laboratory (ORNL) on February 21, 1989. The visit was part of a PRECARN Associates Inc sponsored feasibility study into active vision navigation of mobile robots. For the last few years the experimental robot used at CESAR is the HERMIES IIb (Hostile Environment Robotic Machine Intelligence Experiment Series IIb) featuring autonomous operation, an on-board NCUBE hypercube computer, and a camera and sonar based sensor system. The latest HERMIES version, series III, was to be delivered the week after our visit and will be much increased in size, with a much better on-board manipulator and more batteries (1000 lbs) for longer autonomous operation. The principal topics of discussion were the HERMIES hardware, the NCUBE hypercube, project management, the manipulator, HERMIES IIb, navigation, the DOE/NE University Program in Robotics for Advanced Reactors, a suitable platform for our ARK-1 (Autonomous Robot for a Known Environment), and collaboration. With respect to the last point they are actively seeking international collaboration through their NE program and would welcome collaboration with us.

BACKGROUND

As part of a PRECARN Associates Inc sponsored feasibility study into the use of computer vision for the navigation of mobile robots, a visit was made to the Centre for Engineering Systems Advanced Research (CESAR) at Oak Ridge National Laboratory (ORNL).

PRECARN Associates Inc is a non-profit consortium of Canadian companies and research institutions set up to sponsor pre-competitive R&D into artificial intelligence (AI) and robotics. At present there are seven feasibility studies underway into various aspects of AI and robotics. It is expected that most of the studies will be finished by early summer and advance to the research stage by this fall.

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Our study, "Active Vision Navigation of a Mobile Robot in a Known Environment", has as a first goal to build a robot that can navigate in a known indoor environment using computer vision as its main sensor. The expertise of the university groups involved in our project is in computer vision so that most of the theory developed during this project will be in this area. The main aim of the project is to transfer theory to application. The vision theory being applied in mobile robot projects is behind that of the theoretical vision community, so that as long as there is progress in vision theory, there will be an opportunity to do research. The motivation for Ontario Hydro to be involved in this project is the applications that we have for mobile robots, mainly in the radioactive areas of our CANDU stations. This would include both inspections and environmental sampling. AECL is interested for the same reasons as Ontario Hydro, since its primary business activity is the sale of CANDUs. However, since Advanced Systems is set up as a separate business unit within AECL providing industrial robotic and vision systems, it is also interested in the commercial possibilities of both mobile robots and computer vision. The possible commercial applications of mobile robots outside the nuclear industry would include sentry robots, inspections in other large industrial facilities such as petroleum refineries, floor cleaning, hospital and in-home care for the sick, fire fighting, flexible manufacturing and, if we look far enough in the future, personal robots.

VISIT TO ORNL

Our host for the visit was Reinhold Mann, Leader of the Advanced Computing and Integrated Sensor Systems Group in the Robotics Program and Program Manager for the US DOE/NE University Program in Robotics for Advanced Reactors (see below). We also had conversations with C.R. Weisbin, Director of the Robotics and Intelligent Systems Program (RISP), J.R. Jones, F. Pin, C. Glover and J. Schreyer.

Appendix A is an article from IEEE Expert, which outlines their HERMIES IIb program. Appendix B is an article from Proceedings of the ANS Third Topical Meeting on Robotics and Remote Systems, Charleston, South Carolina, March 13-16, 1989, describing the HERMIES III program.

Handouts obtained during this visit are:

- R.C. Mann, R.C. Gonzalez, D. Tesar, J.S. Tulenko and D.K. Wehe, DOE/NE University Program in Robotics for Advanced Nuclear Reactors, Program Plan: FY 1987 - FY 1992, DOE/OR-884/R1, 1988.
- D. Majumdar (Ed.), Artificial Intelligence Applications in the Nuclear Industry, DOE/ID-10191, UC-523, 1988.
- Centre for Engineering Systems Advanced Research Publications List - January 1989.
- IEEE/RSJ International Workshop on Intelligent Robots and Systems '89, Call for Papers.
- DOE/NE Robotics Program (brochure).
- Robotics and Intelligent Systems, Oak Ridge National Laboratory (brochure), 1987.
- B.L. Burks, G. de Saussure, C.R. Weisbin, J.P. Jones and W.R. Hamel, Autonomous Navigation, Exploration, and Recognition Using the HERMIES-IIb Robot, IEEE Expert, pg 18, Winter 1987 (attached as Appendix A).

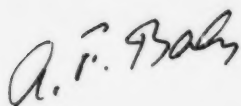
A summary of the conversations in areas not covered by Appendix A or B is attached as Appendix C. The topics covered are:

- HERMIES III
- The NCUBE Hypercube
- HERMIES IIb
- Hardware
- Navigation
- Management
- The DOE/NE University Program in Robotics for Advanced Reactors

They are actively pursuing collaboration with other countries through the DOE/NE program. They would welcome cooperative efforts with us and would be willing to have people from our project make extended visits to their laboratory.

Approved:

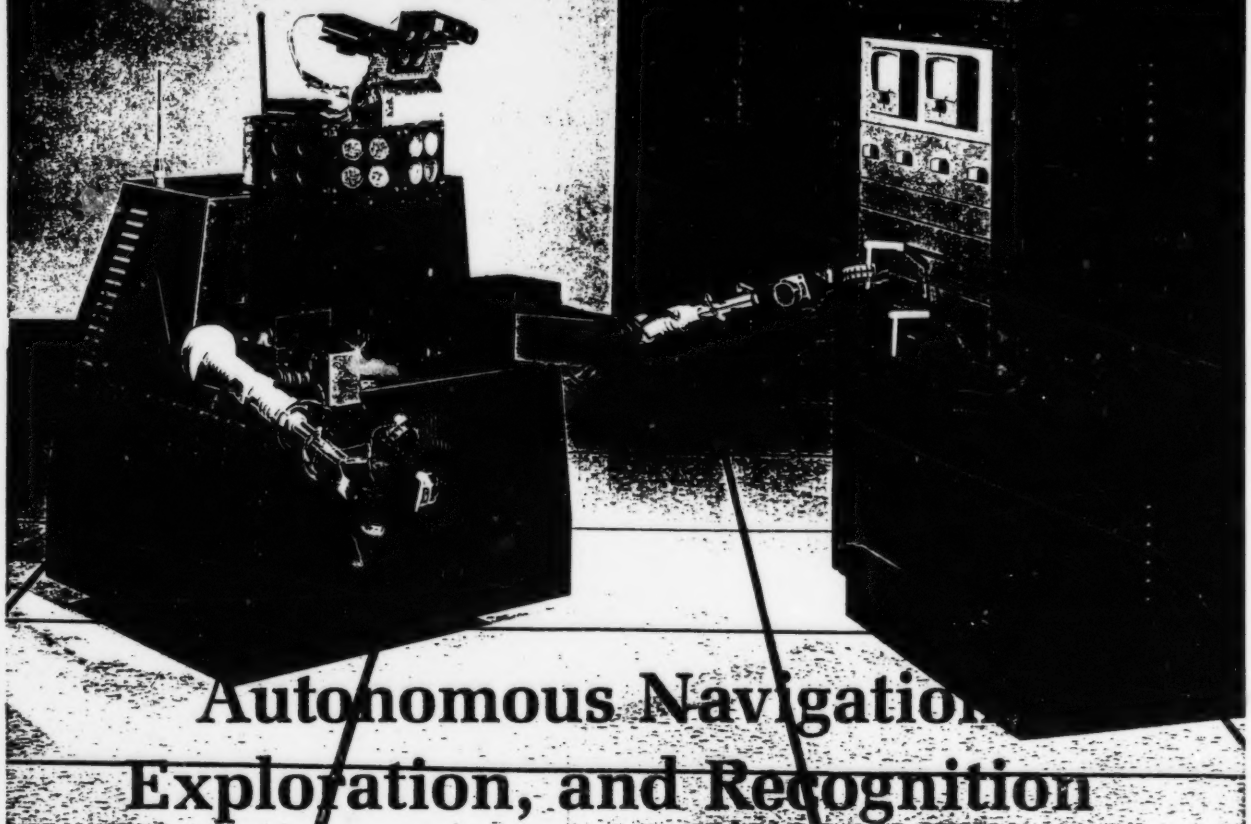
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Autonomous Navigation Exploration, and Recognition Using the HERMIES-IIB Robot

B.L. Burks, G. de Saussure, C.R. Weisbin, J.P. Jones, and W.R. Hamel

Oak Ridge National Laboratory

Developing an autonomous mobile robot capable of navigation, surveillance, and manipulation in complex and dynamic environments is a key research activity at CESAR—Oak Ridge National Laboratory's Center for Engineering Systems Advanced Research. Our current focus is the autonomous mobile system called HERMIES-IIB pictured above.

HERMIES-IIB (hostile environment robotic machine intelligence experiment series IIB) is the latest member in a series of progressively more capable and sophisticated robots. The first HERMIES robots provided valuable experience in planning, world modeling, sensor perception, and communication, but the intensive computations and high-level decision making in these experiments were performed off board in computers linked by radio with the robot.¹⁻³ HERMIES-IIB stresses computational autonomy;

hence, the need for powerful on-board computing capabilities. HERMIES-IIB research has focused on visual perception, goal recognition, and navigation in unknown dynamic environments. HERMIES-IIB manipulators are too primitive to perform tasks requiring significant strength or high precision; however, a complementary research program within CESAR addresses problems in advanced control and motion dynamics with a flexible arm (CESARM) to be incorporated in HERMIES-III.⁴

We will present a concise review of related research, describe HERMIES-IIB and its most important components in some detail, discuss some current research goals, and describe a proof-of-principle demonstration illustrating some tasks HERMIES-IIB can perform. Finally, we will review HERMIES-IIB's present limits and outline directions of future research.

Related research

Autonomous mobile robot research has been underway for over 20 years. Between 1966 and 1972, for example, Nilsson developed and studied Shakey—one of the first mobile automata.⁵ And even then, the chief problems were recognized to be perception (particularly visual perception), world modeling, and problem solving.

In recent years, research efforts have aimed in several directions. In particular, the autonomous land vehicle (ALV) project seeks to develop a vehicle operating at relatively high speeds in outdoor environments such as fields and roads.^{6,7} Such robots require massive computational power and powerful sensors to

adapt their perception/control systems to (1) the high speed of motion, and (2) the many possible outdoor environments. For these reasons, ALV robots are currently rather bulky vehicles.

Other research groups are working with smaller mobile robots, designed to operate mostly indoors or in relatively controlled outdoor environments. These smaller and usually less expensive robots provide a testbed for research in perception, planning, dealing with unexpected occurrences, and goal recognition. In this category belong the LAAS robot Hilare,⁸ the CMU robots,^{9,10} the Stanford,¹¹ SRI,¹² and Purdue¹³ robots; and MIT's MOBOT-1,¹⁴ MOBOT-2,¹⁵ and CESAR's HERMIES-IIB. Other large projects include those of JPL¹⁶ and FMC.¹⁷

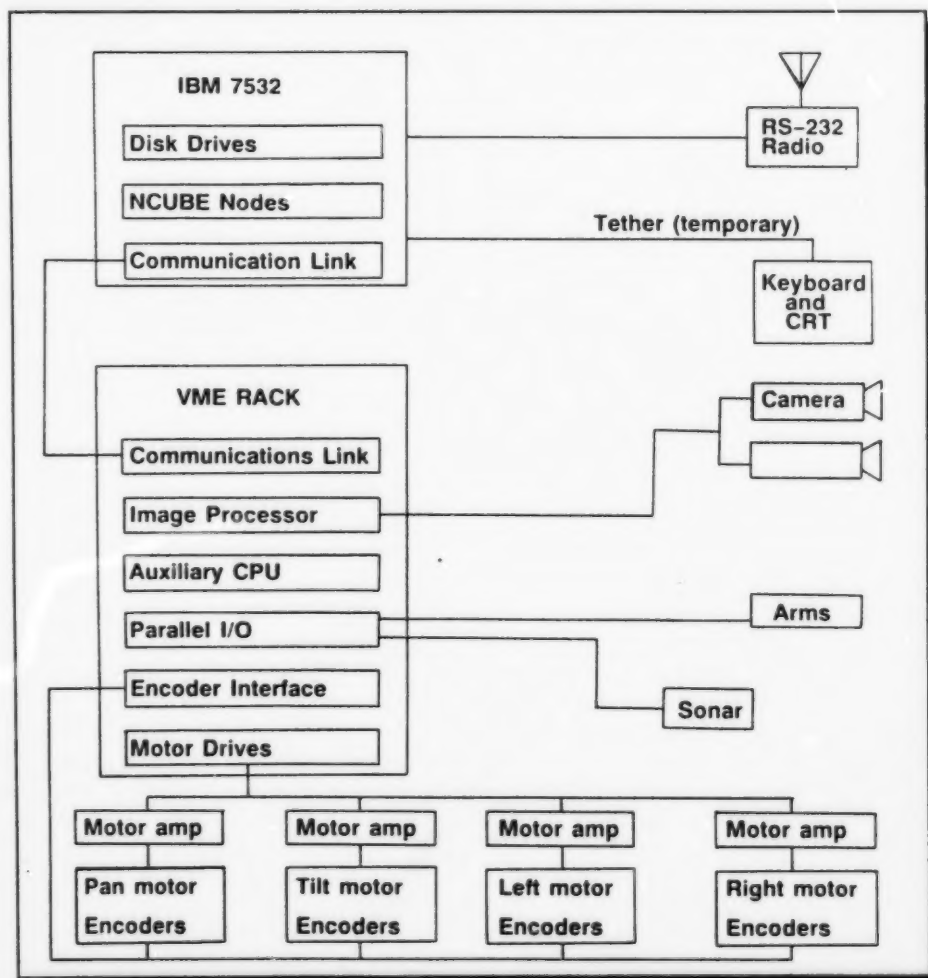


Figure 1. A schematic of the computer hardware, sensors, motors, and peripheral devices for HERMIES-IIB.

HERMIES-IIB: A general description

We designed HERMIES-IIB as a research tool. Considerable flexibility has been incorporated into its design so that features can be added or modified as research requires; for instance, additional sensors can be accommodated and the flexible computer architecture can be reconfigured if desired.

Effectors and sensors. HERMIES-IIB is a self-powered robot system consisting of a wheel-driven chassis, dual manipulator arms, on-board distributed concurrent processors, and a directionally controlled sensor platform. The robot is propelled by a dual set of independent wheels having common axle alignment and driven by separate DC gear head motors powered by pulse-width modulated servo amplifiers. The wheels can move forward or backward to a maximum speed of 0.6 meters per second with ramp up and down. The robot's position can be controlled in an open-loop fashion to a precision of about 0.1 percent for each linear movement, and about 0.1 degrees per rotation using real-time monitoring of the wheel encoders.

Two on-board computers and other electronic equipment are located in an enclosure mounted above the drive chassis. These two computers are stacked with the larger IBM 7532 mounted on slides just above the batteries and drive chassis components in the robot body's rectangular lower part. A VME rack is located above the IBM 7532 in the robot frame's trapezoid-shaped upper part. A dual-arm manipulator torso is mounted above the IBM 7532, forward of the VME rack and on the outside of the robot's "skin." The manipulators are five-degree-of-freedom units manufactured by Zenith/Heathkit and used on the Hero home robot. The torso assembly for the arms also includes a shoulder pitch motion for each arm. The two-arm shoulder assembly has a total of 13 degrees of freedom, including rotation of the robot torso.

The sonar sensing system, an array of Polaroid range finders, consists of 25 individual transceivers—each with a maximum range of 7.75 meters. Digitizing circuitry restricts range resolution, which is equal to 2.5 centimeters (the unit of analog to digital conversion). In six 2×2 matrix clusters, 24 of these sonar transducers are mounted and operated as phased-array range-finding elements to reduce the effective sonar beam from approximately 30 degrees for the individual transducers to about 12 degrees for the

phased-array clusters. Five of these clusters are mounted in a ring on the periphery of the rotatable robot head; the sixth cluster is mounted on a tiltable platform attached to the head. High speed servodrives enable the head to be stepped quickly—the time required to scan the sonar ring over a 180° region in front of the robot is seven seconds. The remaining sonar transceiver (not pictured in this article) is located on the front side of the robot, near the mid-section and between the manipulators. It serves as a collision avoidance sensor during navigation.

A video data acquisition system forms the heart of the machine vision hardware. The system uses two Sony CCD black-and-white cameras at present, one of them equipped with a wide-angle lens. Frame acquisition is via a Maxvideo system from Datacube. It consists of 512×384 pixels with 8-bit gray-value resolution.

Several communication devices send data to and receive data from HERMIES-IIB. We can use these devices to initiate and monitor computer programs running on the on-board processors. The communication devices include an ESTEEM RS-232 radio made by Remote System Technology, and a Hawkeye wireless TV transmitter.

The computer architecture. Figure 1 diagrams the computer layout for HERMIES-IIB. This layout centers around two computer systems—an IBM 7532 loaded with NCUBE nodes, and a VME computer rack.

The IBM 7532, an industrial version of the IBM AT, provides mass storage with a 20M-byte hard disk and a 1.2M-byte floppy disk as well as a 2M-byte RAM. Six AT-style expansion slots and two XT-type expansion slots are available on the computer's back plane. Four of the eight slots are used for I/O devices and memory expansion, while the other four slots are available for NCUBE parallel processing boards. A keyboard and CRT may be temporarily connected to the computer for algorithm development or to start application programs. We disconnect the keyboard and CRT when performing experiments, and conduct computer communication via the RS-232 wireless modem connected to a serial port on the IBM. The IBM is loaded with an Intel 80286 CPU and, at present, with two NCUBE boards—each containing four processor nodes. We can readily expand the number of NCUBE nodes to 16 by utilizing the remaining two expansion slots.

Communication between the IBM 7532 and the VME is by an 8-megabaud (8×10^6 bits) parallel link

made by the Bit-3 computer company, with a transfer rate of 1M byte per second (8 bits = 1 byte).

The VME rack is a 20-slot double-high industrial rack providing the link to HERMIES-IIB hardware. Twenty slots provide plenty of room for controlling the robot's effectors and sensors and leave adequate space for subsequent additions. Figure 2 shows a schematic of the VME subsystem's present configuration.

The computer programs. The IBM 7532 may be operated as an IBM AT running MS-DOS or as an NCUBE host running the AXIS operating system.

Computer programs controlling the robot's behavior are mostly written in C and can be organized into four classes: the HERMIES primitives, the expert system and associated navigation routines, the image analysis routines, and the control and integration programs that reside on the NCUBE host. The expert system may be executed from either MS-DOS or AXIS; however, all of the image analysis routines have been developed for execution on the NCUBE concurrent processing computer. Before implementing these codes on the robot, we use a computer program that emulates the response of the robot for off-board development of the expert system rule base.

The HERMIES primitives, a set of utility routines, control the sensors and effectors and can be called from other programs. Two examples of HERMIES primitives are

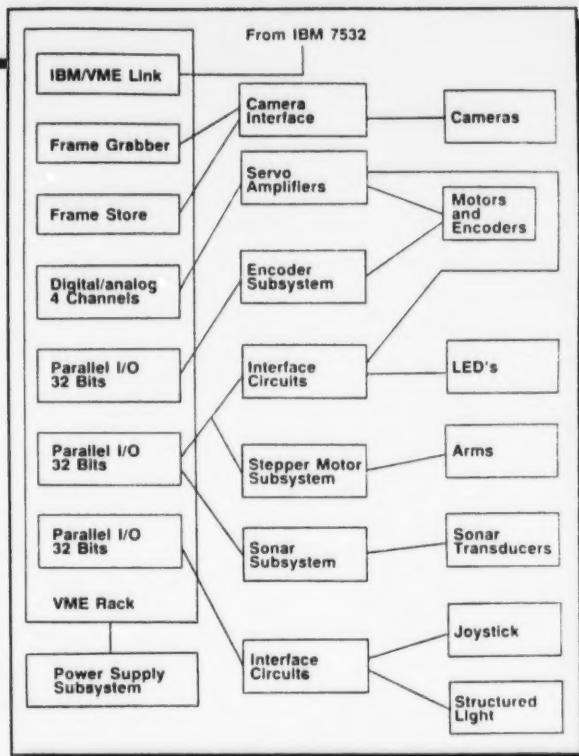


Figure 2. A schematic of the VME subsystem, associated sensors, and peripheral devices for HERMIES-IIB.

int Sonarb(*X*)

a function that returns the sonar reading from Unit *X*, and

*f*move (*f*,*i*)

a command that causes the robot to move forward *f* feet and *i* inches.

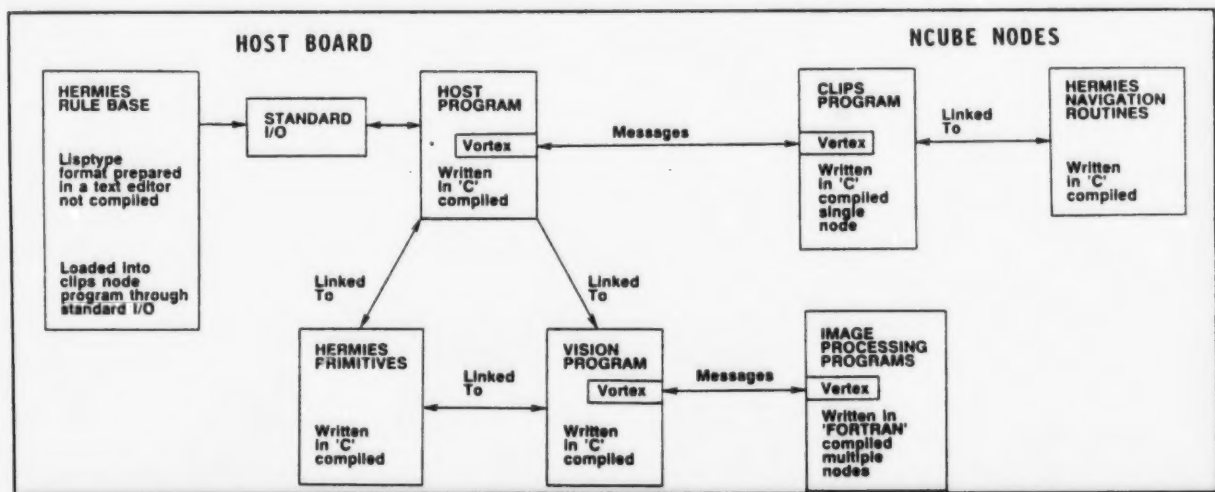


Figure 3. A diagram of the software structure for HERMIES-IIB, illustrating the interlinkage of programs on the IBM 7532 and NCUBE parallel-processing nodes.

HERMIES-IIB CESAR LAB ORNL

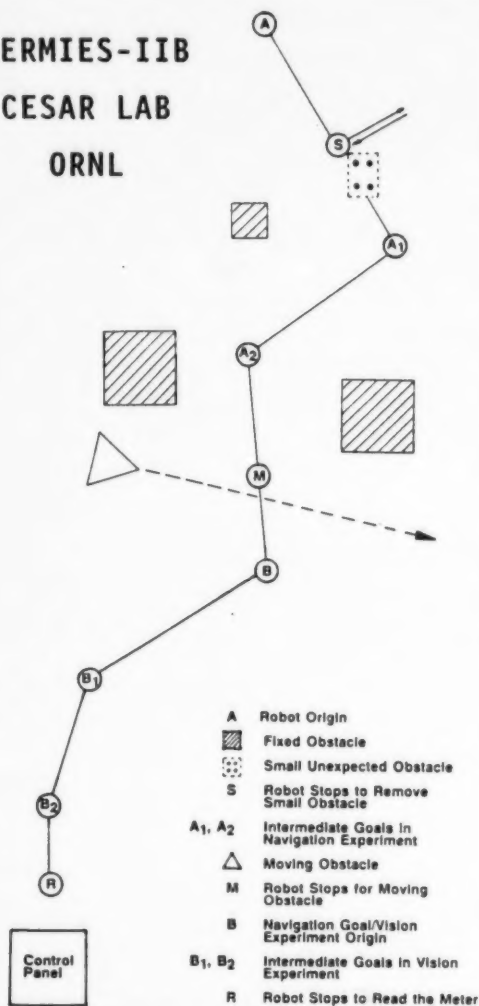


Figure 4. A layout of the experimental area for HERMIES-IIB. The robot navigates from point A to point B, stopping at intermediate goals A₁ and A₂ and responding to dynamic obstacles at points S and M. The robot moves from point B to the control panel, stopping at intermediate goals B₁ and B₂. At point R, the robot is close enough to read the meter.

We obtained valuable experience in perception, world modeling, planning, monitoring the execution of plans, diagnosing unexpected occurrences, and replanning with the first two HERMIES robots.³ In this earlier research, where an RF link to an external computer system controlled the robot, it was determined that using an expert system combined with a number of modular procedures provided a convenient and powerful method for controlling robot behavior. The expert system performs high-level decisions and diagnoses unexpected occurrences. When standard procedures are required such as avoiding or removing an obstacle or mapping an area, the expert system can call the appropriate procedure, which executes until

completed or until an unexpected event generates an interrupt that returns control to the expert system.

For HERMIES-IIB, we prepared a Lisp-type format rule base in a text editor. This rule base controls high-level decisions and can call on C-compiled navigation procedures. The rule base is loaded in an expert system shell called CLIPS and linked to navigation procedures.¹⁸ CLIPS and the navigation routines currently run on one NCUBE node. Messages are passed from the NCUBE node to a host program under the NCUBE operating system AXIS. This host program is linked to the HERMIES primitives on the VME rack.

Figure 3 diagrams the overall configuration of these programs.

Research goals and implementation

Autonomous mobile robots deal with the empirical world, which is never fully predictable; consequently, the robot must continually monitor its environment to perceive and diagnose unexpected occurrences. Moreover, the real world's dynamic and unpredictable nature requires that the robot frequently readjust its plan to changing conditions.

Visual perception and the many computations associated with machine perception, plus frequent replanning in real time, necessitate large amounts of computer processing on board the robot. To satisfy this requirement, HERMIES-IIB is equipped with an NCUBE hypercube supercomputer as well as several other processors (described in the previous section). Therefore, an important HERMIES-IIB research theme is the optimization of overall computer architecture.

A second research topic concerns adapting the NCUBE structure to the rapid analysis required for visual perception and pattern recognition. Still another research goal seeks to improve and make more robust numerous sensing, world modeling, planning, and monitoring processes that we developed in earlier HERMIES versions—processes that must be organized into a consistent control system optimizing robot behavior.

We developed and implemented a demonstration to focus our research, to prove the correctness of our general approach, and to better identify areas for further experimentation. We describe this demonstration below.

Figure 4 illustrates a typical environment for testing HERMIES-IIB. The robot starts from an arbitrary ini-

**HERMIES-IIB is the latest
in an ongoing series
of progressively more capable
and sophisticated robots.**

tial location, denoted by A on the Figure. The coordinates of this initial location A and of a subgoal (location B) are sent to the robot via the RF link. The robot must navigate from A to B, avoiding or removing several types of static and moving obstacles. From location B, HERMIES-IIB must find a mock-up control panel, move up to the panel, and read an analog meter. It is assumed no obstacles exist between location B and the panel. The robot must perform all this autonomously.

HERMIES-IIB starts by making a wide-angle sonar scan of the environment and planning a collision-free path to the reachable point closest to B. As the robot moves toward its destination, sonar apparatus scans the area ahead of the robot. If sonar detects an unexpected obstacle on its path, the robot stops within two feet of the obstacle, diagnoses its nature, and takes appropriate action. Table 1, taken from the expert system rule base, lists illustrative obstacle characteristics and corresponding actions.

Table 1. Diagnosis and action on unexpected obstacles.³

Obstacle characteristic	Action to take
1. Stationary and over three feet tall.	1. Start the navigation algorithm from the current position.
2. Stationary and under three feet tall.	2. Move forward to the obstacle, pick it up with the manipulator arm, put it to one side, and proceed to the original destination. Anything shorter than three feet is guaranteed to be light enough to lift.
3. Has moved out of the way.	3. Proceed to the original destination.
4. Is moving away from the robot.	4. Wait for the obstacle to clear the path and proceed to the original destination.
5. Is moving toward the robot.	5. Check to the left and right with sonar. If clear, move out of the way; if both sides are blocked, go back to the starting position and recheck escape routes to the left and right.

When HERMIES-IIB reaches location B, the vision system searches for the mock-up panel in the following manner: The robot obtains gray-value images of the scene, using the camera with a wide-angle lens; it then converts these to binary images using a threshold based on the average gray value as determined from the image histogram. This proved a reasonably robust method since the control panel and its immediate vicinity do not produce complicated gray-value distributions. HERMIES-IIB searches the binary images to identify groups of pixels that are connected (contiguous and like-colored). Each binary image component is labeled along with component features such as size, aspect ratio, and moment of inertia. The robot compares this list to a description of the control panel generated from a priori information on the geometric relationship among objects (meters and switches) on the panel's front. If one binary image component approximates the expected features of the panel, then the robot moves toward this image component and the steps outlined so far are repeated. The robot continues to move forward until it is close enough that binary image components identified as meters are larger than a preset size.

The camera with the wide-angle lens was calibrated using the simple pinhole camera model (which assumes that each point in the image plane can be connected to the corresponding world point using a straight line through a pinhole displaced from the center of the image by a distance equal to the focal length of the lens). Hence, the robot infers distance information from a priori knowledge on relative sizes of objects identified in the scene.

Once it detects one of the analog meters on the panel at a predetermined size, the system begins to process images from the camera with no wide-angle lens. It searches the region of the binary image identified as a meter to find groups of pixels that form lines. Since the meters have two needles (one is a preset or limit needle), it searches the images to find two lines with a common origin. The system uses a Hough transform to convert the needle position data from Cartesian coordinates to (r, θ) values. The meter read-

Continued on page 26

For advanced control and motion dynamics, HERMIES-III incorporates a flexible arm.

ing is determined by comparing the needle angle to a table of angle-versus-ampere values. The accuracy of the reading deteriorates if the camera is not facing the meter squarely; therefore, as the robot is maneuvered toward the control panel, the image-processing algorithm calculates both linear and angular moves to advance the robot until it's centered in front of the panel.

The programs used by the vision system demonstrate the successful integration of image processing and analysis algorithms on the concurrent multiprocessors of the eight-node NCUBE hypercube on board the robot. These programs feature a new component-labeling algorithm and a Hough transform algorithm with load balancing to be described in detail elsewhere.¹⁹

The successfully implemented demonstration just described validates some concepts of HERMIES-IIB and suggests areas requiring further research. In particular, this experiment proves the feasibility of placing on board the robot all the computing power needed for sensor analysis, planning, and control—at least with respect to the experimental scenario described in this article. The experiment also validates utilization of the NCUBE supercomputer to process in parallel the many algorithms required for rapid scene interpretation.

We need further research to better integrate information from the different sensors and the decision-making programs into one more unified structure: At present, HERMIES-IIB can navigate among moving obstacles using only its sonar sensors, or can navigate using vision—but only in essentially obstacle-free regions. Clearly, better integration of these two navigation modes is desirable. Another area of ongoing research concerns discovering and learning environmental properties. We propose to have our robot discover a system's dynamic properties by manipulating controls on a panel and observing the resulting changes on panel meters. **E**

Acknowledgments

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References

1. C.R. Weisbin et al., "HERMIES-I: A Mobile Robot for Navigation and Manipulation Experiments," *Proc. Robots 9 Conf.*, Vol. 1, Detroit, Mich., June 1985, pp. 1-41.
2. W.R. Hamel et al., "Autonomous Robots for Hazardous and Unstructured Environments," *Proc. Robots 10 Conf.*, Vol. 5, Chicago, Ill., Apr. 1986, pp. 9-20.
3. C.R. Weisbin, G. de Saussure, and D.W. Kammer, "Self-Controlled: A Real-Time Expert System for an Autonomous Mobile Robot," *Computers in Mechanical Engineering*, Sept. 1986, pp. 12-19.
4. W.R. Hamel, "Manipulator Technology: The Critical Element of Useful Autonomous Working Machines," *Intelligent Autonomous Systems Int'l Conf.*, Amsterdam, The Netherlands, Dec. 1986.
5. N.J. Nilsson, "Shakey the Robot," Tech. Report 323, SRI AI Center, 333 Ravenswood Ave., Menlo Park, Calif. 94025, Apr. 1984.
6. M. Turk et al., "Video Road Following for the Autonomous Land Vehicle," *Proc. IEEE Int'l Conf. Robotics and Automation*, Vol. 1, IEEE Service Center, 445 Hoes La., Piscataway, N.J. 08854, Mar. 1987, pp. 273-279.
7. Y. Goto and A. Stentz, "Mobile Robot Navigation: The CMU System," *IEEE Expert*, Winter 1987.
8. G. Giralt, R. Chatila, and M. Vaisett, "An Integrated Navigation and Motion Control System for Autonomous Multisensory Mobile Robots," in *Robotics Research*, M. Brady and R. Paul, eds., MIT Press, Cambridge, Mass., 1984, pp. 191-214.
9. J.L. Crowley, "Coordination of Action and Perception in a Surveillance Robot," *IEEE Expert*, Winter 1987.
10. H.P. Moravec, "The Stanford Cart and the CMU Rover," *Proc. IEEE*, July 1983, pp. 872-884.
11. D. Kriegman, E. Triendl, and T. Binford, "A Mobile Robot: Sensing, Planning, and Locomotion," *Proc. IEEE Int'l Conf. Robotics and Automation*, Vol. 1, IEEE Service Center, 445 Hoes La., Piscataway, N.J. 08854, Mar. 1987, pp. 402-408.
12. S. Rosenschein and L. Kaelbling, "The Synthesis of Digital Machines with provable Epistemic Properties," *Proc. Conf. Theoretical Aspects of Reasoning About Knowledge*, Asilomar, Calif., Mar. 1986, pp. 83-98.

13. A.C. Kak et al., "Experiments in the Integration of World Knowledge With Sensory Information for Mobile Robots," *Proc. IEEE Int'l Conf. Robotics and Automation*, Vol. 2, IEEE Service Center, 445 Hoes La., Piscataway, N.J. 08854, Mar. 1987, pp. 734-740.
14. R. Brooks, "A Robust Layered Control System for a Mobile Robot," *IEEE J. Robotics and Automation*, Apr. 1986, pp. 14-23.
15. R. Brooks, "A Hardware Retargetable Distributed Layered Architecture for Mobile Robot Control," *Proc. IEEE Int'l Conf. Robotics and Automation*, Vol. 1, IEEE Service Center, 445 Hoes La., Piscataway, N.J. 08854, Mar. 1987, pp. 106-110.
16. D. Gennerly et al., "Sensing and Perception Research for Space Telerobotics at JPL," *Proc. IEEE Int'l Conf. Robotics and Automation*, Vol. 1, IEEE Service Center, 445 Hoes La., Piscataway, N.J. 08854, Mar. 1987, pp. 311-317.
17. D.T. Kuan and U.K. Sharma, "Model-Based Geometric Reasoning for Autonomous Road Following," Vol. 1, *Proc. IEEE Int'l Conf. Robotics and Automation*, IEEE Service Center, 445 Hoes La., Piscataway, N.J. 08854, Mar. 1987, pp. 416-423.
18. Computer program CLIPS, NASA Johnson Space Flight Center, distributed by COSMIC Software Information Services, University of Georgia, Computer Services Annex, Athens, Ga. 30602.
19. J.P. Jones, "A Concurrent On-Board Vision System for a Mobile Robot," to appear in *Proc. Third Conf. Hypercube Concurrent Computers and Applications*, Pasadena, Calif., Jan. 1988.



Barry L. Burks—a staff scientist in Oak Ridge National Laboratory's Engineering Physics and Mathematics Division—is primarily responsible for mobile robot design and operation at the Center for Engineering Systems Advanced Research. He received his MS, and his PhD in nuclear physics, from the University of North Carolina at Chapel Hill.



Gerard de Sausture—a staff scientist in Oak Ridge National Laboratory's Engineering Physics and Mathematics Division—has worked for over 30 years in experimental nuclear physics. Currently, he splits his time between nuclear physics and research in strategy planning and machine intelligence at CESAR and is also an honorary professor at the University of Tennessee. He received his PhD in experimental physics from MIT.



Charles R. Weisbin is this issue's guest editor. His biography and photograph (taken together with HERMIES-IIIB) appear in the Guest Editor's Introduction.



Judson P. Jones—a staff scientist in Oak Ridge National Laboratory's Engineering Physics and Mathematics Division—conducts research primarily in concurrent computation and machine vision at the Center for Engineering Systems Advanced Research. He received his PhD in visual neurophysiology from the University of Pennsylvania.



William R. Hamel heads the telerobotics systems section at Oak Ridge National Laboratory's Instrumentation and Controls Division. He is also a principal investigator at the Center for Engineering Systems Advanced Research. His technical interests include dynamic systems analysis and controls, manipulator design, and mechanical nonlinear systems analysis. Before joining the staff at ORNL, Hamel worked for TRW Systems and for Union Carbide Corporation. He received his MSME from Oklahoma State University, and his PhD in mechanical engineering from the University of Tennessee.

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APPENDIX B

DEVELOPMENT OF THE HERMIES III MOBILE ROBOT RESEARCH
TESTBED AT OAK RIDGE NATIONAL LABORATORY

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ABSTRACT The latest robot in the Hostile Environment Robotic Machine Intelligence Experiment Series (HERMIES) is now under development at the Center for Engineering Systems Advanced Research (CESAR) in the Oak Ridge National Laboratory. The HERMIES III robot incorporates a larger than human size 7-degree-of-freedom manipulator mounted on a 2-degree-of-freedom mobile platform including a variety of sensors and computers. The deployment of this robot represents a significant increase in research capabilities for the CESAR laboratory. The initial on-board computer capacity of the robot exceeds that of 20 Vax 11/780s. The navigation and vision algorithms under development make extensive use of the on-board NCUBE hypercube computer while the sensors are interfaced through five VME computers running the OS-9 real-time, multitasking operating system. This paper describes the motivation, key issues, and detailed design trade-offs of implementing the first phase (basic functionality) of the HERMIES III robot.

1. BACKGROUND

The HERMIES III (Fig. 1) mobile robot¹ marks the first opportunity to investigate the integration of full omnidirectional mobility with 7-degree-of-freedom manipulation in a human scale test environment. Mobile robotics research experiments began at the Oak Ridge National Laboratory (ORNL) in 1983 with the first HERMIES (Hostile Environment Robotic Machine Intelligence Experiment Series). A testbed for the investigation of navigation algorithms because ORNL's Center for Engineering Systems Advanced Research (CESAR) Laboratory had already been named a U.S. Department of Energy (DOE) center of excellence for research in intelligent machines, the

opportunities were available for advancing activities in autonomous mobile robots. By 1986, the third robot in the series, HERMIES IIB, had been deployed, integrating the navigation and vision research with sufficient on-board computer capability to permit autonomous operation. These experiments are described in detail in refs. 2-5.

Some of the capability of HERMIES IIB is apparent from its extensive computing capability (Fig. 2). The use of the 16-node NCUBE hypercube concurrent computer allows the on-board vision system to function in a time frame commensurate with experiment requirements. The rule-based guidance system is implemented on a separate set of nodes within the same NCUBE. The specific tasks are assigned to each node so that the load is more efficiently balanced for computationally intense operations.

The limitations of HERMIES IIB in the areas of manipulation, computation, mobility, and physical capacity led to the design of a human-scale, autonomous platform capable of integrating the CESAR Research Manipulator⁶ (CESARm) (Fig. 3) with advanced mobility into a totally autonomous system capable of operating in a human-scale work envelope. HERMIES III is the latest step in demonstrating the application of the research sponsored by DOE to potentially hazardous and/or secure environments common in energy-production facilities. The robot has a full 7-degree-of-freedom manipulator mounted on a 2-degree-of-freedom mobile platform.

The implementation of sophisticated mobile robot control software on board is made possible by including CCD video cameras, sonar, laser range imaging scanner, and encoders. This paper describes the conceptualization, development, and deployment of the HERMIES III mobile robot. As the CESAR research team ports machine intelligence algorithms to the robot, its capabilities will continue to expand greatly with additional sensors and computers likely.

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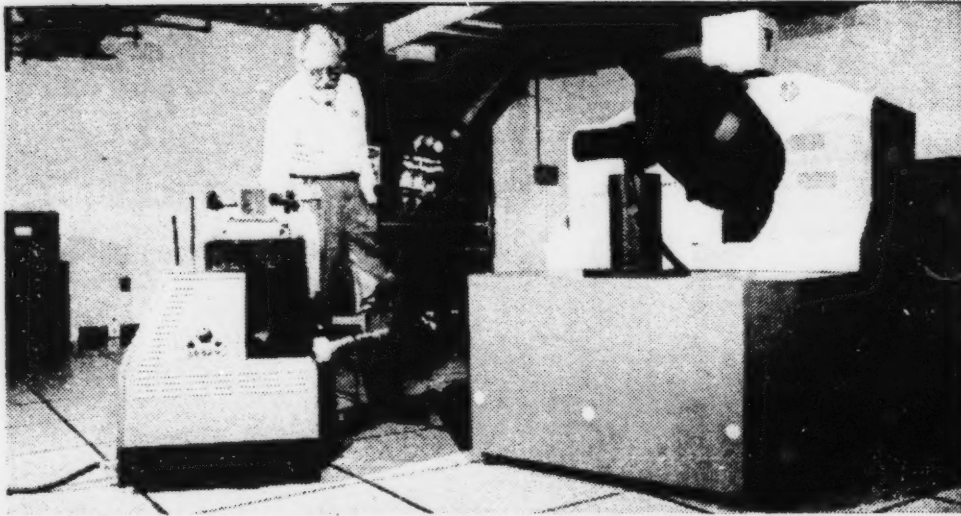


Fig. 1. Full-scale model of HERMIES III (with HERMIES IIB).

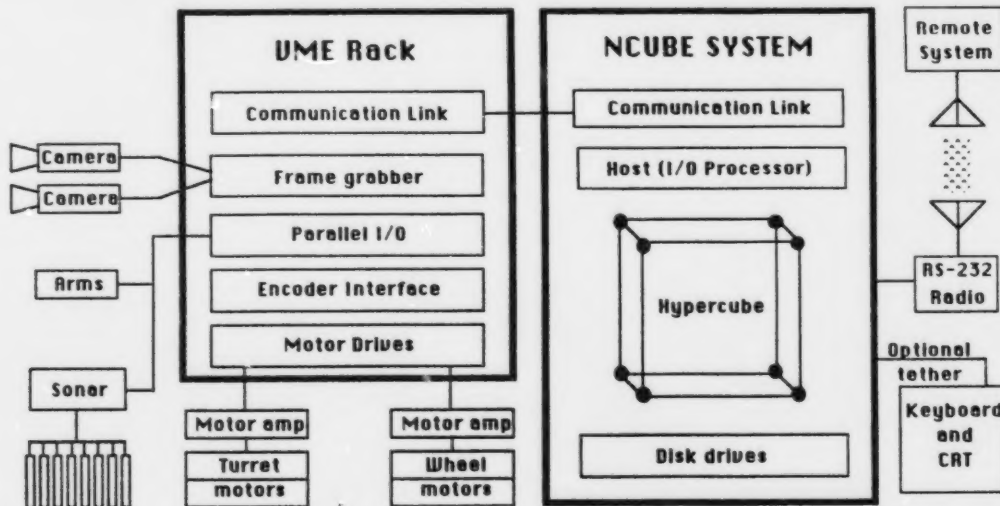


Fig. 2. Block diagram of HERMIES IIB.

II. INTRODUCTION

The implementation of control and navigation algorithms on a mechanical system offers significant advantages over the use of computer simulators. Potential users interested in the application of the algorithms can more easily visualize the development necessary for eventual deployment. Simplifying assumptions required in the use of a simulator are not necessary. One of our goals is to narrow demonstrably the gap between theory and practice by addressing some of the engineering issues necessary in the application of these advanced technologies. Because we are developing a generic testbed, we do not make explicit assumptions about the tasks to be performed by the robot. Commercial applications of

robots depend very much on carefully identifying the tasks to be performed and optimizing the hardware and software to provide a cost-effective package for performing these identified tasks. Our goal in providing a testbed is to outline capabilities and allow the flexibility to redefine tasks using the same basic capabilities. The block diagram in Fig. 4 shows the intended basic capabilities of HERMIES III and how the interconnections are being approached.

The implementation of HERMIES III allows the first experiments involving cooperating, autonomous, and mobile robots. HERMIES IIB and HERMIES III are viewed as resources with dissimilar capabilities that allow research in dynamic task allocation to be advanced.⁷

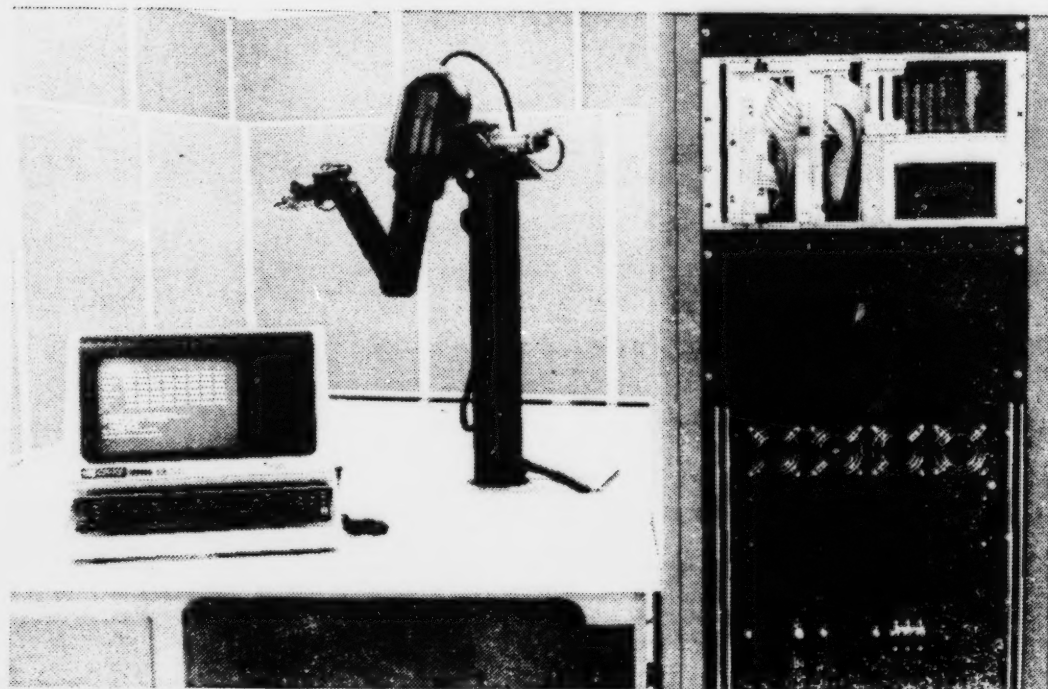


Fig. 3. CESAR research manipulator (CESARm).

III. ATTRIBUTES

HERMIES III is designed to function in a human-size world. The robot has capacities and capabilities simulating those of a human in an environmental protection suit. The design includes a vendor-supplied steer-drive platform capable of planar mobility in any direction and two 7-degree-of-freedom manipulators with parallel jaw grippers. A single manipulator will be mounted in the initial implementation of HERMIES III, with the second added later. A multi-fingered end effector is also planned.

HERMIES III is a multiuser, multitasking environment in which experimenters can validate their algorithms and concepts in a safe and integrated testbed. The implementation of the robot involves research and development in control of wheeled vehicles, human interface, and hierarchical control in addition to the detailed design issues of safety, mobile power, parallel processing, and high speed real-time computer networking. To provide the autonomous capability required, the robot contains five supermicrocomputer (68020) modules running Microware's OS-9 real-time operating system and an industrialized IBM AT incorporating 16 NCUBE hypercube nodes, each with the computing capacity of a VAX 11/780. The design of the robot supports expansion of the NCUBE system to 128 nodes. A power and computer network tether is provided for development activities. Untethered, the robot will be totally autonomous with 3 to 4 h of operation

capability. Figure 5 shows the major components of the robot computer and electronic subsystems.

HERMIES III is designed to be a major user resource at the CESAR laboratory, allowing multiple researchers and technologies to be accommodated without significant interaction. The robot is part of the CESAR laboratory computer network, as shown in Fig. 6, when it is operated in the tethered mode.

This computer network incorporates HERMIES IIB, HERMIES III, and, through appropriate access controls, the ORNL-wide computer network. This arrangement enhances the usefulness of the robot by increasing its accessibility. By implementing the robot using multitasking, multiuser operating systems, we can accommodate multiple research activities while administratively controlling the actual experimentation. By using quick disconnects on the arm, laser range finder, and the video cameras, experimenters can perform bench-top experiments independent of the robot itself. Careful administrative control over the robot itself ensures laboratory safety.

The CESARm represents an active area of robot control research. The kinematic control of this redundant degree-of-freedom manipulator has been reported previously.^{3,10} Integrating the arm into the HERMIES III robot extends the research opportunities to include mobile manipulation.

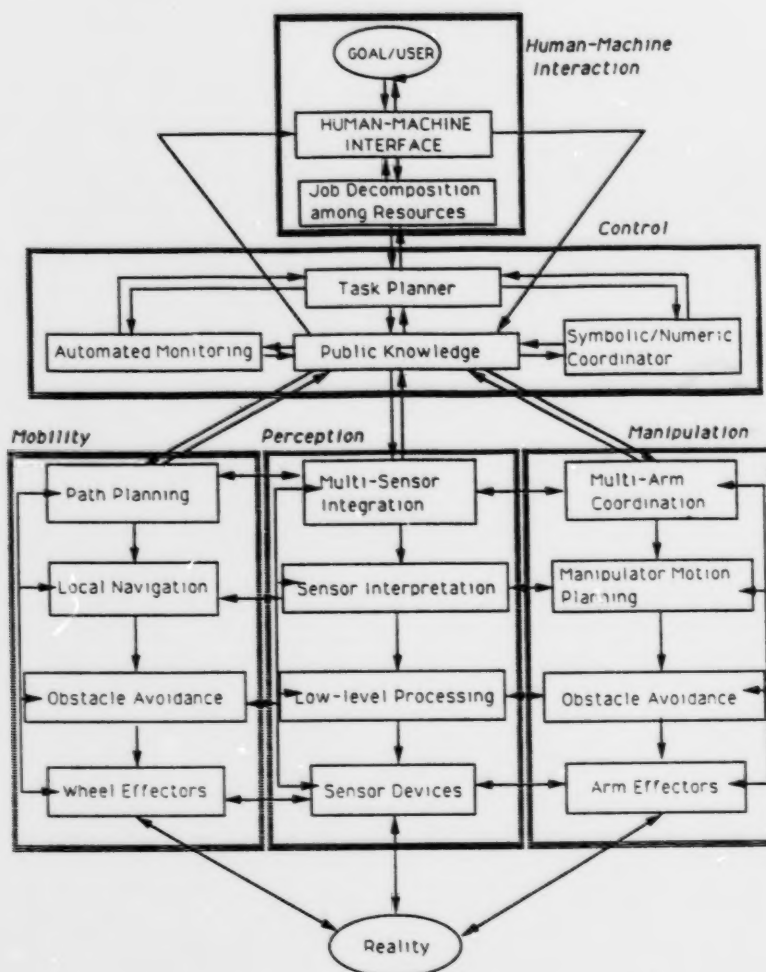


Fig. 4. Block diagram of HERMIES III software architecture.

IV. RESEARCH AGENDA

Our proposed experiments involve the performance of realistic, human-scale tasks in an environment that simulates part of an industrial plant. A network of pipes will be provided with valves of various types and sizes and various meters (such as temperature and flow). A separate control panel will be provided with meters, switches, lights, and buttons, simulating control of part of an industrial process. No water will actually flow through the pipes, but by computer control the meter readings will realistically reflect the valve positions, either for normal operation of the system or for any of a set of possible trouble conditions, such as an increase in temperature or a drop in pressure. This environment is geometrically complex; therefore, it requires integration of dexterous manipulation and platform motion and, sometimes, cooperation among multiple robots so that task objectives can be achieved.

An example of the environment is illustrated by the model in Fig. 7 in which HERMIES III is shown performing manipulations. Environmental and experimental constraints include

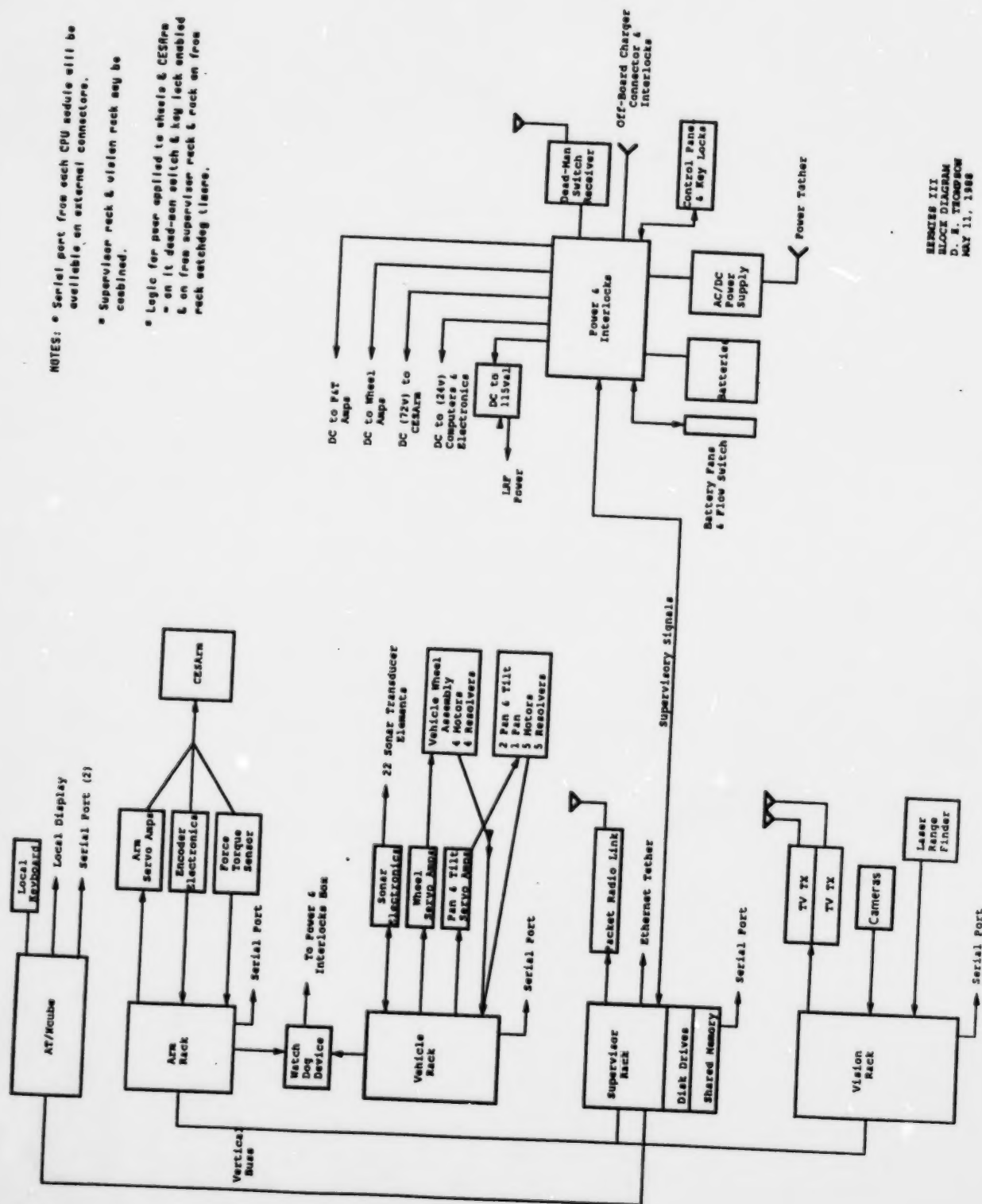
1. multiple valves, pipes, meters; control panel; obstacles on the floor;
2. no exact world model (as-built drawings), just information equivalent to preliminary drawings;
3. valves occluded from view and obstructed;
4. current operability of valves unknown;
5. multiple navigation paths of differing complexity; and
6. completion of some tasks subject to time constraints.

The goal of each experiment in this series is to correct a dangerous condition in the simulated cooling system by navigating to and finding the system, identifying its components, analyzing the problem, and correcting it by manipulating one or more valves and one or more buttons and levers on the control panel.

NOTES: • Serial port from each CPU module will be available on external connectors.

• Supervisor rack & vision rack may be combined.

• Logic for peer applied to wheels & CESArm - on it dead-man switch & key lock enabled & on from supervisor rack & rack on from rack watchdog timers.



HERMES III
BLOCK DIAGRAM
D. E. THOMPSON
MAY 11, 1988

Fig. 5. HERMES III computer and electronic controls.

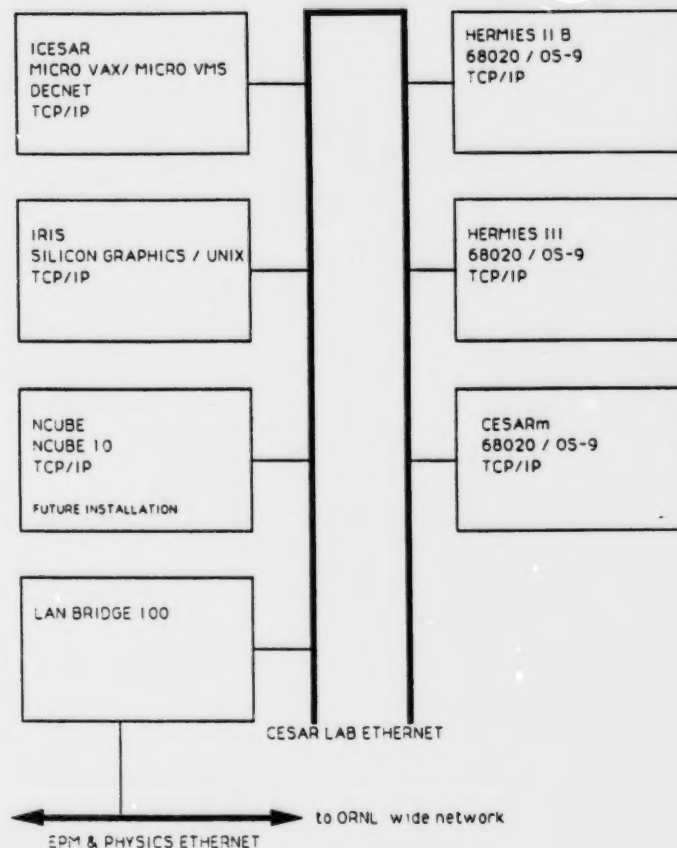


Fig. 6. CESAR laboratory computer network.

The environment (e.g., pipes and meters) has a number of variable parameters so that not one but a range of experiments may be done. The equipment is being constructed so that its parameters can be easily varied. It will be possible to vary the orientation of the valves so that they point up, down, horizontally, or at any other angle, and so that their axes are not necessarily perfectly perpendicular to those of the pipes to which they are attached. The relative positions and orientations of the valve and the obstructing object are variable. If a valve is behind an access window, its position and orientation relative to that window are variable.

V. SENSORS

The robot contains 32 active sonar devices mounted around the circumference of the frame that can be fired individually or in programmed sequence. The sonar devices are used constantly for obstacle detection and for supplementing the data from the other sensors in mapping the environment. The sensors on the arm will include tactile sensing at the gripper and a provision for sensing all the joint angles and the force and torque at the end-effector. The cameras on the robot

provide data for the vision algorithms to ascertain detailed information about the environment. The cameras are mounted in pairs having different focal lengths, one having a wide angle and the other a close-up lens. The high-speed pan and tilt tables provided for the cameras allow them to track the end-effector of the manipulator to facilitate research in vision-guided manipulation.

The recently acquired Odetics-built laser range finder (LRF) provides a capability not previously available in the CESAR laboratory. It is mounted on a pan table atop HERMIES III so that it can be used as the primary sensor for mapping the environment. It provides range and reflectance data in a pixel array 128×128 ray directions within a $60 \times 60^\circ$ field of view. The instrument is designed for an operating range of 0.5 to 20 m (with a range ambiguity past 9.37 m caused by the phase shift at that distance). The laser source is a modulated GaAlAs diode, wavelength 820 nm, with power output adjustable under software control to levels between 1 and 50 mW. At full power and at distances beyond 0.2 m from its window, the LRF meets the Class I (eye safe) safety requirements of the Center for Devices and Radiological Health (U.S. Food and Drug Administration). The LRF

provides a 16-bit word for each ray direction that contains both range and reflectance data. The data are transmitted to the VME-based computer systems via a DR11W parallel interface. An entire scan is completed in ~0.8 s.

The LRF, in conjunction with other on-board sensors, provides data necessary for navigation in a three-dimensional environment and for object recognition for manipulation research. Multisensor integration for navigation uses both range and reflectance data from the LRF as well as sonar and vision data. Other experiments planned involve recognition by the robot of an array of pipes and their attached valves and meters whose exact location is not known priori. LRF data, with their angular resolution of ~0.5°, are of considerable utility in identifying objects and their three-dimensional positions when the data are combined with data from vision.

VI. MECHANICAL DESIGN

Specifications:

Total weight (one arm)	1230 kg (2700 lb)
Batteries	410 kg (900 lb)
48 V at 110 A-h	
24 V at 220 A-h	
Vehicle speed	60 cm/s (2 ft/s)
Vehicle acceleration	120 cm/s/s (4 ft/s/s)
Arm tip speed	300 cm/s (10 ft/s)
Arm weight	160 kg (350 lb)
Arm payload	12.7 kg (28 lb)
Arm reach	137 cm (54 in.)

The chassis for the mobile platform was provided by Spartan Textile Machinery Inc., in Inman, S.C., which supplies wire-guided vehicles for carpet mills in the southern United States. It is rectangular with dimensions of 1.22 m (4 ft) by 1.52 m (5 ft) × 0.6 m (2 ft) high with two steer drive wheels and four corner casters. The frame was designed by the manufacturer with a unique hinging scheme that ensures that all the wheels remain in contact with the floor and continue to bear the load as designed even on a mildly irregular floor surface. ORNL built and added the top frame to support the electronics and safety equipment required for the final product.

Because this robot will be used in a general purpose research laboratory, the safety of the experimenters and observers is a primary concern in the design of the robot. The laboratory has a designated area roped off so that access is restricted. Strobe lights on board the robot warn that power is being applied to the motion actuators and that the robot can therefore move. The power is also interlocked through multiple keyswitches, dead-man interconnects, and watchdog timers verifying that the control computers are ready. Battery charging is done on board with an ac tether. Air flow switches interlock with the charging circuit to ensure adequate ventilation during battery charging.

The speed and acceleration capabilities of the arm dictated the design and fabrication of a special-purpose pan and tilt table. The four available tables have a modular design

that allows the same components to be used in each axis (pan and tilt) of the table. The computer control of the actuators is facilitated by the precision resolvers provided on each axis. The coordinated action of the cameras mounted on the pan and tilt tables with the motion of the arm supports the vision-guided manipulation research.

VII. COMPUTERS AND ELECTRONICS

The basic electrical subsystems on board the robot include power distribution, servo amplifiers, sensor support, controls, and safety. All on-board systems are under the supervision of the VME-based 68020 processor dedicated to on-board monitoring and control.

The power distribution system supplies dc power to all on-board systems through separate 24- and 48-V systems. The dc can be supplied from battery or from on-board power supplies that convert the off-board ac provided through the tether. The robot can operate untethered for ~4 h. The remainder of the time it is powered by converters supplying 6000 W of dc from the ac power tether. An inverter provides 120 VAC power during untethered operation.

The on-board computer system is a multitiered array of computers consisting of a hypercube system and multiple, dedicated 68020 processors for low-level control. The hypercube is used in the expert system, vision research, and multisensor integration data reduction algorithms. The computer architecture is modeled after that used successfully on the HERMIES IIB robot.⁴ The NCUBE hypercube is packaged in an industrialized IBM AT chassis with direct access to the VME bus through a Bit 3 VME bus interface module. This arrangement allows direct access to the address space of the VME system, allowing faster access to the sensor data gathered by the VME-based computers. The VME computers directly drive the actuators based on the high-level instructions from the NCUBE algorithms. The diagram in Fig. 5 details the computers and interconnections on board HERMIES III.

The initial software implementation allows access to the sensors and actuators through primitives previously developed for the HERMIES IIB robot. Upgrades provided for the new sensors and actuators allow the high-level software to take advantage of the LRF and the steer-drive mechanism. A control algorithm is provided to allow a high-level interface to the actuators without having to understand the details of the actuator itself. The modularity of the software supports direct connection so that direct control can be achieved as part of the ongoing research in the control of the actuators.

VIII. FUTURE

The ultimate implementation of the robot is open to a number of variables, but the details above outline the current plan. Implementation will be phased so that early functionality can be ensured while maintaining a clear migration path to the ultimate design. The modular design and technology available from previous research in the CESAR laboratory allow us good flexibility without sacrificing uptime.

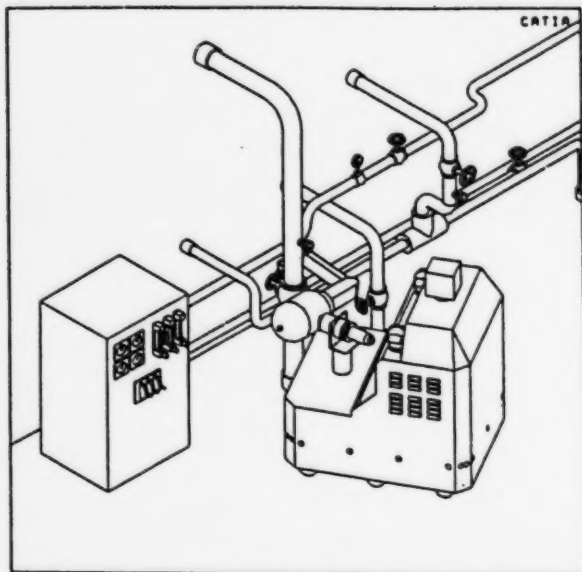


Fig. 7. Model of HERMIES III proposed experiment environment.

As the testbed matures, the research extends to take advantage of the flexibility and capability provided. HERMIES III was designed for easy sensor and computer expansion or revision. Integrating the control of the two available robots (HERMIES IIB and HERMIES III) will provide a significant challenge. Continuing to provide the tools for development so as to provide high-level interfaces to researchers not interested in the details while providing access to low-level actuators in support of control algorithm development will be a key to the success of HERMIES III. Integration of the control of the second arm and the research of the real-time distributed control of the robot represent areas of extensive research interest. Decentralized control is expected to be of considerable interest in future work on the testbed robot. The addition of a multifingered, dexterous end-effector is expected to open up new areas of research in control and integration.

IX. CONCLUSION

The CESAR laboratory at ORNL now has a robotics research testbed that places it in a unique position to research areas of integrated mobility, manipulation, and perception in an unstructured, human-scale environment. The development of the testbed robot has been a significant activity at ORNL and provides insight into the development of mobile robots in general. This paper has detailed the development and integration of electrical, mechanical, and computer systems necessary to provide the required functionality. The availability of HERMIES III in the CESAR laboratory facilitates the ongoing activities involving visiting researchers from universities and other laboratories. Future participation from an even broader range of researchers is anticipated as DOE increases its emphasis on national user facilities and technology transfer.

ACKNOWLEDGMENTS

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REFERENCES

1. C. R. WEISBIN, G. DE SAUSSURE, J. R. EINHSTEIN, E. HEER, and F. G. PIN, "CESAR Research in Autonomous Mobile Navigation and Learning," *IEEE Computer*, December 1988, CESAR-88/59.
2. B. L. BURKS, G. DESAUSURE, C. R. WEISBIN, J. P. JONES, and W. R. HAMEL, "Autonomous Navigation, Exploration and Recognition Using the HERMIES IIB Robot," *IEEE Expert* 2(4): 18-27 (1987).
3. B. L. BURKS and P. F. SPELT, "Ongoing Research Using HERMIES— The Hostile Environment Robotic Machine Experiment Series," Materials Handling FOCUS 88, Georgia Institute of Technology, Atlanta, September 13-14, 1988.
4. W. R. HAMEL, S. M. BABCOCK, M. C. G. HALL, C. C. JORGENSEN, S. M. KILLOUGH, and C. R. WEISBIN, "Autonomous Robots for Hazardous and Unstructured Environments," Proceedings of the Robots-10 Conference, Chicago, April 20-24, 1986, pp. 5-9 through 5-29.
5. J. P. JONES, "A Concurrent On-Board Vision System for a Mobile Robot," Third Conference on Hypercube Concurrent Computers and Applications, 1988.
6. S. M. BABCOCK, W. R. HAMEL, and S. M. KILLOUGH, "Advanced Manipulation for Autonomous Mobile Robots," Proceedings of ANS International Topical Meeting on Remote Systems and Robotics in Hostile Environments, March 1987, pp. 290-297.
7. L. E. PARKER and F. G. PIN, "A Methodology of Dynamic Task Allocation in a Man-Machine System," *Methodologies for Intelligent Systems*, ed. Z. W. Ras and M. Zemankova, New York, 488-495 (1987).
8. R. V. DUBEY, J. A. EULER, and S. M. BABCOCK, "Real-Time Implementation of a Kinematic Gradient Projection Optimization Scheme for Seven-Degree-of-Freedom Redundant Robots with Spherical Wrists," *Journal of Robotics and Automation*, June 1988, CESAR-88/36.

9. R. V. DUBEY, J. A. EULER, and S. M. BABCOCK, "An Efficient Gradient Projection Optimization Scheme for a Seven-Degree-of-Freedom Redundant Robot with Spherical Wrist," Proceedings of the 1988 IEEE International Conference on Robots and Automation, Vol. 1, April 25-29, Philadelphia, pp. 28-36, CESAR-87/42.
10. S. M. BABCOCK, R. V. DUBEY, J. A. EULER, R. L. GLASSELL, R. L. KRESS, and W. R. HAMEL, "Telerobotic Control of the Seven-Degree-of-Freedom CESAR Manipulator," Proceedings of the NATO Advanced Robotics Workshop on Robots with Redundancy, Salo, Lago di Garda, Italy, June 1988.

APPENDIX C

SUMMARY OF DISCUSSIONS AT ORNL

1. HERMIES III

- HERMIES III is the successor to HERMIES IIb. It weighs 2800 lbs with 1000 lbs of batteries and is approximately 1.5mx1.5mx1.5m in size.
- It will have a 7 degree-of-freedom manipulator with a 7:1 weight to pickup ratio and be able to pick up 30 lbs.
- It will have an on-board NCUBE hypercube, with 8 nodes initially and 16 nodes eventually. There will be 4 double high VME racks, with one rack for the sensors and one for the arm.
- It will have a laser range finder on board (\$140k).
- It will be used to perform a cleanup of a simulated chemical spill as part of the DOE/NE program.

2. The NCUBE Hypercube

- This is a computer that is on-board both the HERMIES IIB and the HERMIES III.
- The main criteria for choosing the NCUBE is the low power consumption. The only other candidate that they feel would have a low enough power consumption is the Transputer.
- The NCUBE hypercube can scale up to 1024 processors and NCUBE has fielded 3 such systems.
- The cost of a 64-node board is about \$140K. The total system cost for a 64-node system is about \$250K. The total cost of a 16-node system is about \$50K.
- When you transfer code from a workstation to the NCUBE you must put your algorithms into parallel. Sometimes it is easy and sometimes it is complex. They have written theirs so that the number of processors is an argument. A rule of thumb is that it takes as long to parallelize a piece of code as it did to write it in the first place.
- NCUBE is coming out with a second generation processor soon.

3. HERMIES IIb

- They have had a lot of problems with their sensor turret and their arms. They were too shaky and needed to be professionally designed.
- If they were redesigning HERMIES IIb today they would use the Cybermation K2A platform instead of designing their own.

4. NAVIGATION

- The levels of competence are:
 - Wander around aimlessly avoiding objects.
 - Explore by moving to observed places.
 - Build a map of the environment.
 - Notice changes in the environment.
 - Reason about identified objects and perform tasks with these objects.
 - Formulate and execute plans to change the world.
 - Reason about object behavior and modify plans.
 - A basic R&D topic in perception today is building better maps based on multi-sensor input either from the same or different types of sensors. Another issue is what to do if different sensors give conflicting data.
- The levels of spatial knowledge are:
 - Magellan Level
 - Known world map
 - Optimization of route planning
 - A* like algorithm
 - Columbus level
 - Unknown area
 - Emphasis on obstacle avoidance
 - Ulysses level
 - Navigate in a changing world
 - Emphasis on replanning and world map readjustment

5. MANAGEMENT

- They strongly believe in demos as part of the management process since it seems to attract funding and the process itself is very instructive.
- The skills distribution that they see for this type of project is:
 - Mathematics
 - Expertise in neurophysiology
 - Computer science
 - Experimental physics
 - Support people (BScs in computer science and technicians)
 - Hardware people including a mechanical engineer
 - Doesn't see the need for an AI person

- Staff according to program emphasis
- They usually have about 4 students working with their group.

6. The DOE/NE University Program in Robotics for Advanced Reactors

- This project is supported by the US DOE (Department of Energy) and managed by ORNL. The university partners are the University of Michigan, the University of Tennessee, the University of Florida and the University of Texas and the industrial partners are Combustion Engineering, Odetics, Gulf State Utilities, Florida Power and Light Company, Remotec and Telerobotics International.
- The purpose of this project is to "pursue research leading to the development and deployment of advanced robotic systems capable of performing tasks that are hazardous to humans, that generate significant occupational radiation exposure, and/or whose execution times can be reduced if performed by an automated system" (Report DOE/OR-884 REV. 1 - see above).
- They plan to achieve this by moving from teleoperation to autonomous operation in three generations.
- The target application areas are: nuclear and fossil plants, chemical plants, fire fighting, space operations, underwater activities, defense, and other hazardous activities.
- Some of the projects on-going in this program are:
 - A snake-like articulated body robot capable of crawling over obstacles; the target application is nuclear plants.
 - A raster-scanning radiation camera.
 - A sensor-driven stationary manipulator for tasks associated with the operation of a mock-up control panel.
 - The design of a modular robot manipulator.
 - Algorithms based on constructive solid geometry for robot world modelling based on data from a laser range camera.
 - The HERMIES III and other ORNL will be a test bed for the testing of much of the university work.
 - They are actively seeking cooperation with other countries.